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Sensory properties of foods functionalised with milk proteins

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ABSTRACT

The growing interest in a healthy lifestyle has motivated consumers to ask for functional foods capable of conferring additional benefits to simple nutrition. However, such functional products must also meet the sensory features required by the market to be competitive and acceptable for consumption. In this regard, milk proteins have been very successful due to their nutritional quality and their versatility as food ingredients. Here we have reviewed the current knowledge on the use of native or customised milk proteins to improve the nutritional and techno-functional properties of functional foods. We also explore the interactions between milk proteins and other matrix components (i.e., volatile compounds and phenolic compounds), focusing on the effects of their addition on the physicochemical and sensory properties. Furthermore, we discuss the applications of milk proteins (whey and casein-based ingredients) in both dairy and non-dairy foods. Milk proteins are versatile and can be used to develop customised milk protein-based ingredients with the most desired functional properties. Their binding properties with volatile and phenolic compounds improve the flavour perception, helping to reduce fat, sugar and salt in foods. Such interactions between milk proteins and food matrix components can change the protein structure imparting new functional properties. Depending on the food formulation and purpose, the amount and type of milk protein to be used are good variables to consider in order to optimise the technological and sensory properties of food.

1. Introduction

The growing awareness of the relationship between diet and health has led consumers in both developed and developing countries to choose functional food products, which in addition to conventional nutrition are able to provide protection and prevention against nutrition-related diseases and improve physiological functions (Díaz, Fernández-Ruiz, & Cámara, 2020). Thanks to the communication of a positive image on health, functional foods represent a product marketing strategy, although the functional component is not the only one that determines the purchase intent (Menrad, 2003). In fact, there are also factors concerning sensory and hedonistic properties, as well as convenience attributes that drive the consumer's purchasing choice. Hence, the improvement of sensory properties and flavour perception of functional foods is economically relevant and, as such, needs to be well understood and considered to formulate competitive functional products. A range of food applications for whey proteins and caseins have been explored in detail in Section 4. These include dairy products such as yogurt (Lesme, Alleaume, et al., 2020), ice cream (Feyzi, et al., 2020) and cheese (Wen, et al., 2021), as well as bakery products (Camargo, et al., 2018; Gani et al., 2015). These applications provide not only an improved nutritional profile, thanks to the increased protein content and reduced fat, calories, and cholesterol, but also acceptable sensory properties.

Milk proteins are among the most popular and valuable ingredients used for the development of functional foods. Whey proteins and casein have a high nutritional value due to their amino acid profile. These proteins, in fact, have a high biological value, with a protein digestibility-corrected amino acid score (PDCAAS) of 1, which indicates a high-quality protein source in terms of balance of essential amino acids and their digestibility (Phillips, 2023). Moreover, the digestible indispensable amino acid score (DIAAS), a more recent system compared to PDCAAS, that mainly focuses on the content of essential amino acids and their effective digestibility in the human intestine, has higher values for milk protein, casein and whey protein isolate compared to other protein sources (Wolfe, Baum, Starck, & Moughan, 2018). Proteins obtained from milk also contain other essential nutrients for human metabolism, such as minerals (calcium, zinc, magnesium and phosphorus) and B vitamins (Anand, Som Nath, & Chenchaiah, 2013). Furthermore, they are precursors of bioactive peptides, making them suitable for functional food applications (Mohanty, Mohapatra, Misra, & Sahu, 2016). Whey

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proteins exhibit functional properties, such as solubility, gelling, emulsifying and foaming properties (Wolfe, et al., 2018), while caseins are used as ingredients for their emulsifying, thermostability and coagulation properties. Milk proteins also provide a source of bioactive peptides resulting from their hydrolysis, which have positive effects on human health, such as improved calcium absorption and antioxidative activity.

Recently, Yiğit, Bielska, Cais-Sokolińska, and Samur (2023) published a review mainly focusing on the health benefits of whey protein added to food and the functional properties of whey protein in the processing of functional products. They addressed the antioxidant, anti-inflammatory and anti-hypertensive functions of whey proteins, as well as their role as gelling, thickeners, emulsifiers and encapsulating agents. We agree with the authors on the need for in vivo studies to validate the beneficial effects of whey proteins on human health, especially regarding the derived bioactive peptides. However, some aspects involving milk proteins in foods have not been covered, i.e., the use of caseins has not been explored, as well as the interaction that milk proteins undertake with the components of the food matrix and the related implications on the sensory perception of functional foods. In the current review we aim to fill this gap by addressing these aspects, particularly the interactions that milk proteins can establish with phenolic and volatile compounds, providing this information in the first part of the work. We believe that this information is useful for directing the development of novel functional foods with the addition of milk proteins with better sensory and nutritional properties. In the second part of the review, we summarised the applications of milk proteins in dairy and non-dairy foods, explaining the reason for their use and the main effects on physicochemical and sensory properties.

2. Functional properties of milk proteins

From the chemical-compositional standpoint, in cow's milk, 20% of milk proteins is represented by whey proteins, soluble globular proteins composed of beta-lactoglobulin (β-Lg) and alpha-lactalbumin (α-La) at a ratio of 3:1, bovine serum albumin (BSA), immunoglobulins, and some enzymes such as bovine lactoferrin, lactoperoxidase, alkaline phosphatase and lysozyme. The other part of the milk protein fraction is represented by micellar caseins (CN), grouped in α_{S1}-CN, α_{S2}-CN, β (+γ)-CN and κ-CN which occur in the approximate proportions of 4:1:4:1 (Livney, 2010). Chymosin is an enzyme present in the rennet used to coagulate milk caseins during the production of many types of cheese. This coagulation process involves the partial hydrolysis of the caseins and the consequent formation of several peptide compounds. Thus, other minor components (present in rennet whey) are glycomacropeptide (GMP) and other soluble rennet proteolysis products which are released from κ-casein in the first step of enzymatic cheesemaking. Some proteases intrinsically present in milk, such as blood plasmin, carry out a post-translational proteolysis generating a range of small (proteose--peptones) and large (Y-caseins) peptides (Swaisgood, 1995b). For further information on the composition of cow's milk proteins and amino acids as well as enzymes, refer to chapters 5 F (Swaisgood, 1995b) and 5H (Swaisgood, 1995a), respectively, in the Handbook of Milk Composition, where these topics are discussed in detail.

Several advantages incentivise the use of milk proteins as ingredients to develop functional foods. Milk proteins are safe to consume, have a high biological value and can be obtained as by-products of the dairy industry, like whey proteins. Furthermore, both caseins and whey proteins have interesting functional properties and acceptable sensory characteristics, limiting the impartation of possible off-flavours to functional foods (Livney, 2010).

Caseins are rheomorphic proteins endowed with a unique structure that imparts them distinctive functional properties. Overall, the structure of casein micelles is complex, with various models proposed to explain their assembly and stability. Several publications have summarised the different models proposed for the casein micelle structure (Holt, 1992; Horne, 2006; McMahon & Oommen, 2013). These models include coat-core model, the subunit (submicelles) model, and the internal structure model. The stability of the micelle is ensured by the presence of a surface layer of hydrophilic C-terminal peptides of κ-CN, which acts as a steric stabiliser (Horne, 2006). This outer "hairy layer", which comprises the glycosylated part of κ-CN casein, helps to maintain the integrity of the micelle providing colloidal stability. Additionally, the micelle's stability is influenced by factors such as the presence of calcium phosphate and the interactions between casein subunits. This micellar aggregation is facilitated by phosphoserine sites on the outer surface of submicelles, which are linked together by calcium, a divalent cation acting as a bridge (Lucey & Horne, 2018). The presence of high quantities of the amino acid proline in the micelle structure prevents the formation of secondary structural motifs common to other proteins (e.g. whey protein). Furthermore, the high level of proline residues leads to a high affinity of casein micelles for phenolic compounds, resulting in binding to polyphenols via hydrogen bonds between the peptide carbonyl and the phenolic hydroxyl along with other interactions between phenolic rings and hydrophobic amino acid residues (Rashidinejad et al., 2017). Instead, the two major whey proteins, which account for about 70–80% of total whey proteins, are β-Lg (18.3 kDa) and α-La (14.2 kDa) (Wolfe, et al., 2018). β-Lg, the main whey protein of ruminant milk (~ 65%), is classified as lipocalin that can bind small hydrophobic ligands (Kontopidis, Holt, & Sawyer, 2004). β-Lg is a globular small protein with 162 amino acid residues that fold into an 8-stranded, antiparallel β-barrel structure (Kontopidis, et al., 2004). It has a 3-turn α-helix on the outer surface and a ninth β-strand flanking the first strand. α-La, composed of 123 amino acids and 4 disulfide bridges, is a metalloprotein that binds two calcium ions between four aspartic acid residues (Wolfe, et al., 2018). The strong binding of calcium results in a high heat stability and a relatively high denaturation temperature. Another structural difference with β-Lg lies in the absence of free thiol group that can serve as the starting-point for a covalent aggregation reaction. Consequently, pure α-lactalbumin does not form strong gels during denaturation and acidification and, compared to β-Lg, does not form disulphide bridges with sulphur compounds (Wagner, Biliaderis, & Moschakis, 2020). The different structure and composition between whey protein and casein result in different binding properties with food matrix components such as phenolic and volatile compounds, which are covered in detail in section 3.

Whey proteins and caseins exert a different effect on human metabolism and physiology, as they are digested and absorbed differently, releasing different amino acids and peptides. Caseins are classified as slow-digesting proteins that forms a gel-like structure in the stomach which helps to slow down the release of amino acids into the bloodstream, while whey proteins are fast-digesting proteins. Some human health benefits of whey protein and casein, such as contribution to satiety, postprandial blood glucose control, antihypertensive effects and body protein synthesis, have been reviewed elsewhere (Nongonierma & FitzGerald, 2015).

A more detailed summary of the beneficial effects of milk proteins and their digestive products is shown in Fig. 1. The hydrolysis of milk proteins, by enzymatic treatment, microbial fermentation or in vivo gastrointestinal digestion, releases amino acid sequences, called cryptides, with bioactive functions (Chalamaiah, Ulug, Hong, & Wu, 2019). Peptides with different bioactivities, such as anti-inflammatory, antimicrobial, antioxidant, immunomodulatory activities have been produced by the fermentation of milk proteins by some bacterial and yeast strains (Manzoor, Singh, & Gani, 2022). Yiğit et al. (2023) concluded that whey protein supplementation in the human diet may play a positive role in the control of insulin response, reduction of postprandial glycemic response, and increase of meal satiety. Peptides derived from whey protein hydrolysis exerted antimicrobial, ACE-inhibitory (antihypertensive) and hypocholesterolemic activity demonstrated mainly through in vitro assays. In addition, casein phosphopeptides are used, both in foods and supplements, to improve the absorption of calcium, iron and zinc (Miquel & Farré, 2007), exerting benefits for bone

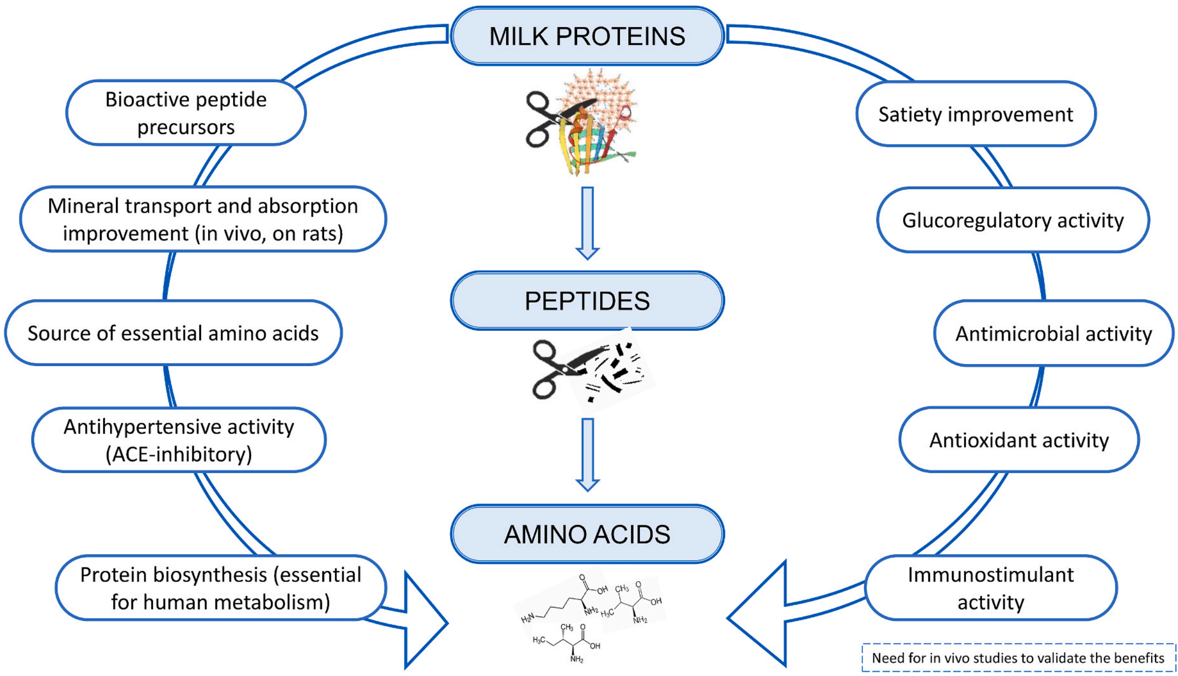

Fig. 1. Health properties of milk proteins and their hydrolysates.

calcification (Liu, et al., 2018). Digestion of β-casein can lead to the formation of β-casomorphins. Among the casomorphins, the one that has attracted the most attention is β-casomorphin-7 (BCM-7), a heptapeptide with opioid effects. BCM-7 is released from β-casein A1, B, and C, genetic variants in which Pro^{67} (present in A2 β-CN variant) is replaced with His, by the action of pepsin, pancreatic elastase, and leucine aminopeptidase (Swaisgood, 1995b; Thiruvengadam, Venkidasamy, Thirupathi, Chung, & Subramanian, 2021). Studies on the bioactive effects of BCM-7 are still ongoing, and the results are conflicting. Thiruvengadam et al. (2021) have recently reviewed the potential health effects of BCM-7, which include opioid-like activity, increased antioxidant level, suppression of oxidative stress, immunological effects by regulating the immune system and inflammatory response, and other effects such as appetite regulation. However, some adverse effects have also been reported, such as implications in the development of cardiovascular disease, allergy and autism, but the validity of such associations is still a subject of debate and research.

Other works have identified several peptides with antioxidant (DPPH and ABTS tests) and antihypertensive activity, generated from casein and whey proteins of milk fermented by *Lactobacillus reuteri* strains (Cui, et al., 2022), or released by gastrointestinal digestion after the consumption of milk (Caira, et al., 2022), cheese (Abedin, Chourasia, Phukon, Singh, & Rai, 2022) and ice cream (Carrizzo, et al., 2021). However, although in vitro approaches are useful as screening and for discovering novel peptide sequences with potentially bioactive functions, their bioactivity should ideally be confirmed in human or in animal studies. For further reading, the review by Daroit and Brandelli (2021) covers some in vitro and in vivo (mainly on mice) effects of bioactive peptides derived from milk proteins.

Food processing also affect the nutritional and functional properties of milk proteins by imparting new functions. For instance, heat treatments are combined with emerging technologies, such as ultrasound, high-pressure treatment, pulsed electric fields, supercritical fluid extrusion and radio frequency, to modify the structure of whey proteins and caseins to influence their technological behaviour, e.g. cause their aggregation and gelling (Nunes & Tavares, 2019). An improvement in the emulsion stability and a reduction of the particle size distribution of whey protein isolate was obtained after an acidic pH 2-shifting-ultrasound treatment (20 kHz and 600 W for 30 min) (Jiang, et al., 2022). Ji, Yang, and Yang (2022) improved the DPPH radical scavenging capacity and reducing power of quercetin by partial unfolding of whey protein concentrate subjected to a mixed pre-treatment of heat, ultrasound and pH shifting. In particular, the treatment at pH 7.4 after heating at 80 °C for 30 min ensured the strongest binding affinity of quercetin-protein complexes, with the smallest particle size and the largest ζ-potential. In goat milk, the heat treatment at 65 °C for 30 min and 85 °C for 15 s caused an increase in particle size, turbidity, ζ-potential, and surface hydrophobicity of whey protein (X. Zhao et al., 2020). These increases improved the emulsifying activity index, water-binding capacity, oil-binding capacity, foaming capacity and foam stability of whey proteins. Finally, the protein conformation, changed by food processing, can affect the binding properties of milk proteins, with volatile compounds or with other food compounds, e.g. polyphenols (Nunes and Tavares, 2019). These protein conformation changes modulate the sensory perception of functional foods.

3. Milk protein and food matrix interactions

Milk proteins can interact with food constituents, i.e. volatile compounds and polyphenols, influencing their delivery and sensory perception during the consumption of food (Zhang, Kang, Zhang, & Lorenzo, 2021). The main implications caused by the interaction of milk proteins with volatile and phenolic compounds are reported in Fig. 2. These interactions are important factor that can affect the consumers' acceptability.

3.1. Volatile compounds

Understanding the interactions between volatile compounds, responsible for the odour and aroma of food, and milk proteins is useful in the applications of milk proteins to produce functional foods, where they can act as a flavour carrier and enhance flavour perception during oral processing of functional food. In fat-free foods, volatile compounds are released from the food matrix more rapidly (Feyzi, et al., 2020), with less persistence during and after consumption. The same authors reported that, from in vivo studies, the use of whey proteins increased the in-mouth persistence of aromatic compounds and that the structure and chemical composition of volatile compounds represent decisive factors

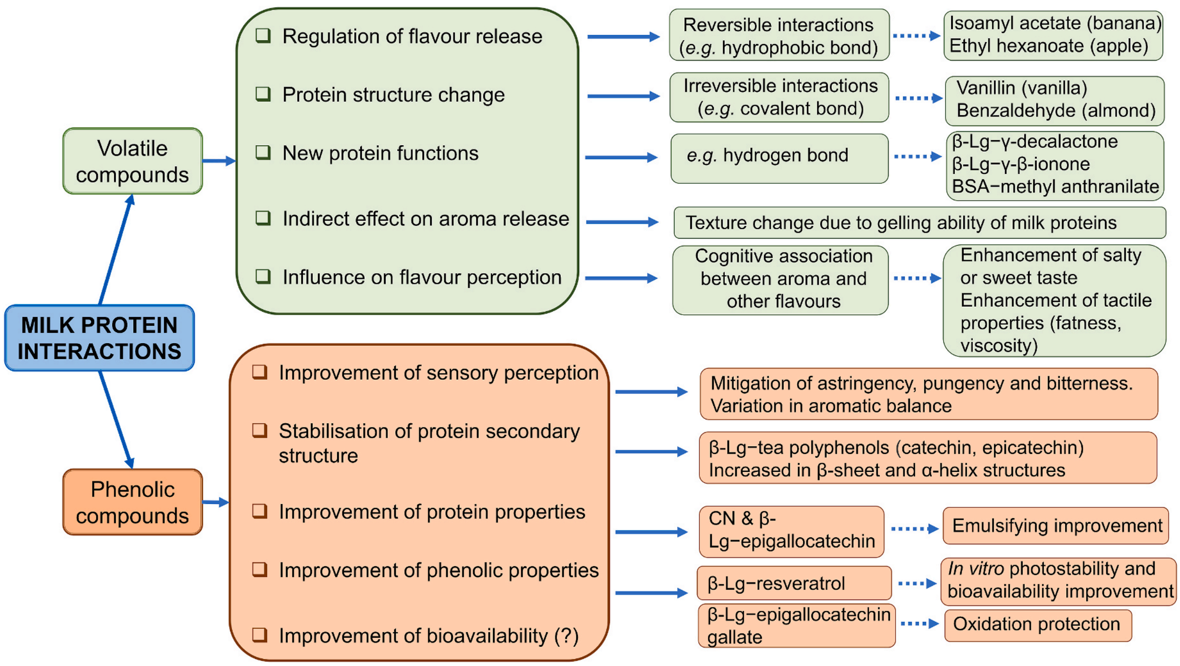

Fig. 2. Effects of the interaction of milk proteins with volatile and phenolic compounds. β-Lg: beta-lactoglobulin; BSA: bovine serum albumin; CN: caseins.

in the interaction with whey proteins. The denaturation of whey proteins, and hence the change of their structure, leads to new functional properties of the proteins, expanding their food application. Meanwhile, the foaming properties of milk proteins (80:20 casein:whey protein ratio) added in a fat-free dairy matrix modified the aroma release compared to the same unfoamed milk proteins (Thomas, et al., 2022). The fat-free dairy matrix was formulated with the addition of ten volatile compounds, and it was found that less hydrophobic compounds such as allyl isothiocyanate (alliaceous odour typical of Brassicaceae) and 2-dodecenal (citrus odour) obtained good aroma retention while the more hydrophobic ones such as thiazoline, ethyl butanoate, methyl salicylate and camphor were released more intensely from foamed matrix.

The aroma release kinetics is also indirectly affected by the change in the texture of matrix caused by the addition of milk proteins (Lesme, Rannou, Famelart, Bouhallab, & Prost, 2020), which can help compensate for the loss of functionality due to the reduction of ingredients such as fats in low-fat foods. In fact, milk proteins, binding volatile compounds and modifying the texture of food (gelling), influencing the perception of flavour due to the lower mass transport (Kühn, Considine, & Singh, 2006).

Such ability to bind volatile compounds also depends on the type of milk protein, i.e. whey or casein, or more specifically β-Lg, α-La, α_{S1}-CN and β-CN (Kühn, Zhu, Considine, & Singh, 2007). Whey proteins has been shown to have a greater influence than caseins in reducing the in mouth aroma release (Denker, et al., 2006). Depending on the chemical-physical characteristics of the volatile compounds and the milk protein, reversible or irreversible bonds can occur (Kühn, Delahunty, Considine, & Singh, 2009), although the most frequent that occurs is the reversible (hydrophobic) one (Kühn, Considine, & Singh, 2008). This reversible bond can help in regulating the release of flavours from functional foods developed with milk proteins. Esters (isoamyl acetate and ethyl hexanoate) and ketones (2-heptanone) had slower release rates in β-Lg solutions than only water (Jung & Ebeler, 2003) (Fig. 2). In model solutions developed using different individual milk proteins or whey protein isolate and sodium caseinate, the binding capacity of 2-nonanone decreased in the order BSA > β-Lg > α-La > α_{S1}-CN > β-CN (Kühn, et al., 2007). Moreover, the quantity of 2-nonanone bound to whey protein isolate was higher than that of sodium caseinate. In fact, thanks to hydrophobic binding sites, native β-Lg readily binds methyl ketones (2-heptanone, 2-octanone, 2-nonanone) through hydrophobic interactions and this binding strength is reduced by denaturation (non-native form of β-Lg). BSA exhibits high affinity for various volatile compounds due to the presence of multiple protein binding sites, as observed for methyl ketones (Jung, De Ropp, & Ebeler, 2002) and lactones (Guth & Fritzler, 2005). Regarding the chemical composition of volatile compounds, aldehydes (*trans*-2-nonenal and 1-nonanal) reacted covalently with whey protein isolate, while the quantity of 2-nonanone released into the headspace was higher due to non-covalent hydrophobic interactions (Kühn et al., 2008). In fact, milk proteins can bind the carbonyl group of volatile compounds, such as vanillin (vanilla odour) and benzaldehyde (almond odour), irreversibly (Guichard, 2006; Kühn et al., 2006) limiting their release and perception. On the other hand, the irreversible bond with some aldehydes, such as hexanal, *cis*-2-heptenal and *trans,trans*-2,4-decadienal, developed by the catalytic oxidation of unsaturated fatty acids, could limit and mask the perception of rancid off-flavours in food (Zhang, et al., 2021). Furthermore, interactions between volatile compounds and milk proteins can change the protein structure, as demonstrated by Dinu et al. (2022) on BSA protein and methyl anthranilate interaction. In particular, methyl anthranilate binds BSA through the establishment of hydrogen bonds with arginine^{409}, lysine^{413} and serine^{488} of the Sudlow II site of BSA. This binding interaction induces conformational compactness in the BSA structure, leading to a more compact and stable protein conformation. Thus, this change in structure implies new functional properties, including binding properties, of the protein.

The change in protein structure has been observed in BSA bound to methyl anthranilate, but it is plausible that other major whey proteins, like β-Lg, can undergo similar structural changes because of interaction with volatile compounds. Many works that have studied the interactions between milk proteins, especially β-Lg, and volatile molecules have mainly considered the implication on the release of the volatile molecules responsible for the aroma. Often, in this works, environmental conditions such as pH, temperature, ultrasound or denaturing reagents, are varied to vary the structure (from native to non-native) of the β-Lg and study its effect on aroma retention (Jouenne & Crouzet, 2000; O'Neill & Kinsella, 1987; Xu et al., 2022). However, the interaction between myofibrillar proteins (meat/muscle tissue proteins) and nonanal (typical meat volatile compound) was recently studied (Han, Shen, Zhao, & Sun, 2018), reporting no significant conformational changes deriving from the interaction. On the other hand, information regarding casein subunits and their potential structural modifications in relation to volatile compounds are still lacking and deserve studies in the literature. Thus, further studies are recommended to better understand the role of protein structure change following binding of volatile compounds on flavour release, also considering the role of protein type (e.g. β-Lg, α-La, β-CN etc.) and the type of volatile compound involved in the interaction.

In conclusion, the ability to modulate the aroma release while ensuring the expected flavour of the food makes milk proteins a useful ingredient in low-fat foods. This aspect will be taken up again in the following sections.

3.2. Phenolic compounds

Phenolic compounds are responsible for stimulating astringency, pungency or bitterness during food consumption, and these sensory characteristics are in part caused by the interaction of phenolic compounds with salivary proline-rich proteins (PRPs) via hydrophobic bonds (Huang & Xu, 2021). This interaction involves the precipitation of the protein-phenol complex in the oral cavity and produces astringency or pungency (trigeminal components of flavour perception) usually experienced in foods rich in polyphenols such as coffee, cocoa, wine and tea.

Interactions between milk proteins and phenolic compounds inhibit further interaction with salivary proteins and can mitigate astringency and bitterness (Ares, Barreiro, Deliza, & Gámbaro, 2009; Tagliamonte et al., 2023). Moreover, it has been reported that milk proteins (whey and casein) interacted with salivary mucin glycoproteins affecting the in vitro oral processing of food containing protein emulsion with an aggregating effect of saliva on casein and whey proteins (Çelebioğlu, Lee, & Chronakis, 2020). Whey proteins, through weak interactions, can help reduce astringency and bitterness, while maintaining the same polyphenol profile (Jauregi, Olatujoye, Cabezudo, Frazier, & Gordon, 2016). However, the control of the astringency and bitterness of the polyphenols should not significantly compromise their beneficial activity on humans. Based on the binding affinity of milk proteins with phenolic compounds, the DPPH radical scavenging activity of phenolic compounds could more or less be reduced (Xiao, et al., 2011). The addition of milk proteins reduced the bioavailability of the chlorogenic acid of coffee (A Rashidinejad et al., 2022). Both caseins and whey proteins can bind chlorogenic acid through hydrophobic interactions, hydrogen bonding or van der Waals forces, with β-Lg demonstrating a stronger binding affinity for chlorogenic acid in comparison to other milk proteins, such as α-La and β-CN (A Rashidinejad et al., 2022). Other results on in vivo tests reported no significant differences on human total plasma antioxidant activity (Reddy, Vidya Sagar, Sreeramulu, Venu, & Raghunath, 2005) and polyphenol bioavailability (Roura et al., 2007) from the interaction of phenolic compounds with milk proteins. However, the effect of milk proteins on the bioaccessibility of phenolic compounds in functional foods is controversial (A Rashidinejad et al., 2022).

The presence of phenolic compounds in food can affect the aromatic perception, as well as the aromatic perception can influence astringency and pungency. In wine, the intensity of fruity and floral olfactory perception, typically imparted by esters, decreased when the level of phenolic compounds increased (Goldner, di Leo Lira, Van Baren, & Bandoni, 2011), shifting the aromatic perception from fruity to woody/earthy aroma (Cliff, Stanich, Edwards, & Saucier, 2012). In yogurt, it has been shown that the olfactory perception enhances the astringency and influences their mouthfeel, i.e. a higher retronasal aroma intensity of green apple (obtained from a mixture of amyl acetate, *trans*-2-hexenal, hexanal, ethyl pentanoate and γ-octalactone added at concentrations ranging from 2.2 to 63.2 ppb) decreased the perceived thickness in the mouth (Kora, Latrille, Souchon, & Martin, 2003). Therefore, the addition of milk proteins to functional foods, due to the interaction with phenolic compounds, could affect the trigeminal stimuli and aroma balance, changing the flavour perception.

Several studies have shown that β-Lg is able to interact with tea polyphenols and resveratrol (C. D. Kanakis et al., 2011; Liang, Tajmir-Riahi, & Subirade, 2008), while BSA can interact with different flavonoids including luteolin, apigenin, acacetin, tricin and linarin (L. Fu et al., 2016). Interaction with phenolic compounds can also modify the functional properties of milk proteins. Yuksel, Avci, and Erdem (2010) proposed that the cross-linking between green tea flavonoids and milk proteins could be used for the manufacturing of novel milk products (e.g., yogurt and cheese) with desired textural properties. Indeed, it was later reported that the secondary structure of β-Lg was stabilised, with an increase in β-sheet and α-helix structures, by binding with tea polyphenols (catechin, epicatechin, epicatechin gallate and epigallocatechin gallate) (C. Kanakis et al., 2011). Thermally modified β-Lg has bound epigallocatechin gallate from tea with greater affinity than the native β-Lg. In particular, when epigallocatechin gallate was added to preheated (75–85 °C, 20 min) β-Lg solution during cooling and vortexing, small delivery nanoparticles were formed (smaller than 50 nm, not visible and not perceptible in the mouth), ideal for clear beverage applications. The addition of β-Lg-epigallocatechin gallate nanoparticles ensured considerable protection to the polyphenol against oxidative degradation (Shpigelman, Israeli, & Livney, 2010). In another study, these covalent milk protein-epigallocatechin gallate complexes gave milk proteins better interfacial and emulsifying properties and a higher denaturation temperature (Wei, Yang, Fan, Yuan, & Gao, 2015), improving the physical and chemical stability of a model β-carotene emulsion, where sodium caseinate stabilising the emulsion better than β-Lg.

Regarding the carrier properties, β-Lg and resveratrol interaction has improved the photostability and increased the water solubility of the polyphenol, parameters suggesting a better bioavailability (Liang, et al., 2008). The recognised antioxidant activity and other health benefits (Ebrahimi & Lante, 2021) have focused researchers' interest on the bioavailability of polyphenols bound to milk proteins (Yildirim-Elikoglu & Erdem, 2018). Such interactions can benefit both the techno-functionality of milk proteins as ingredients in functional foods and improve the stability and delivery of bioactives, i.e. by offering protection from oxidation, increasing their stability in the gastrointestinal tract and improving their delivery to colon (Jakobek, 2015).

The development of whey protein particles functionalised with dietary phenols through encapsulation techniques has emerged with the aim of increasing the bioavailability of phenolic compounds (Wu, Hui, Gong, et al., 2021). The formation of nanoparticles between proteins and polyphenols has been shown to improve the bioavailability of phenolic compounds, via enhancing their solubility, preventing their degradation in the gastrointestinal tract, elevating the permeation in small intestine, and even increasing their contents in the bloodstream (Hu, Liu, Zhang, & Zeng, 2017), as well as making them imperceptible in the oral cavity.

In conclusion, milk protein and phenolic compound interactions could be a useful strategy to improve the multisensory flavour perception of food. In addition, the structural changes resulting from this interaction can improve the stability of polyphenols and act as carriers of these compounds in the intestinal tract. However, since the bioaccessibility of phenolic compounds bound to milk proteins is controversial, further studies should be undertaken to this end. This behaviour could depend on the type of phenolic compound and the protein involved in the interaction (hence on their chemical structure), as recently indicated (Cianciosi, et al., 2022), considering that interactions between milk proteins and food matrix components can change the protein structure imparting new functional properties.

4. Milk proteins in functional foods

The functional food market is growing rapidly (Tadesse & Emire,

2020) and consumers are increasingly interested in preventing disease and improving their health status through the choice of functional foods (Küster, Vila, & Abad-Tortosa, 2022).

Milk proteins can be added to foods with the aim of improving their structure, flavour profile, nutritional and other functional properties. Table 1 provides an overview of the application of milk proteins, reporting the type of milk protein used (e.g. whey protein concentrate, whey protein isolate, sodium caseinate, milk protein isolate etc.) in dairy and non-dairy based foods. Here, the relevance of the use of milk proteins as a source of functional ingredients in the food industry has been highlighted, focusing on their impact on sensory properties.

4.1. Dairy foods

Dairy products have a prominent position in the functional food market. In fact, the dairy products market is very segmented, offering probiotic, low-fat, lactose-free, high-protein foods etc. Typically, milk proteins are added to dairy products to partially replace fat, to increase protein content, or to impart desired functional properties. Various forms of whey proteins, including isolate, concentrate, microparticulate whey proteins, have been the main types of milk proteins added to functional dairy products (Table 1).

Table 1
Applications of milk proteins in dairy and non-dairy foods and main results.

Food	Milk protein ingredients	Motive	Main results	References
Dairy-based foods				
Ice cream	Microparticulated whey protein concentrate (Simplesse)	Fat replacement	No significant difference in perception of grassy (*cis*-3-hexen-1-ol) and candy aroma (ethyl-3-methyl-3-phenylglycidate). Peachy and peachy aroma persistence (γ -undecalactone) were perceived stronger in ice cream with milk protein. Less creaminess in low fat ice cream.	Liou and Grün (2007)
Saffron ice cream	Whey protein isolate	Fat replacement	The replacement of fat with whey proteins caused a higher release of safranal in the headspace and mouth cavity.	Feyzi et al. (2020)
Low-fat cream emulsions (19% milk fat)	Whey protein or milk protein isolate	Fat replacement	Higher G′ value (64.8 Pa) for emulsions with milk protein. K-carrageenan addition improved the stability of cream emulsions with milk protein isolate.	Seo and Yoo (2021)
Buffalo milk ice cream	Bioactive peptide developed from the digestion of buffalo milk proteins	Bioactive function	Stable bioactive pentapeptide was generated at high concentrations by in vitro and in vivo gastrointestinal digestion. Blood pressure reduction in murine models.	Carrizzo et al. (2021)
Stirred yogurt	Three milk protein blend ingredients	Fat replacement	Best scores in terms of sensory creaminess for mixture containing microparticulated whey proteins.	JanhØJ et al. (2006)
Yogurt	Microparticulated whey protein	Fat replacement	Microparticulated whey protein with higher ratios of native β-lactoglobulin and α-lactalbumin achieved apparent viscosity of yogurt similar to whole yogurt. Increasing whey protein concentration causes a more compact structure.	Torres et al. (2018)
Plain-type yogurt	Extruded microparticulate whey proteins	Fat replacement	Lower rates of syneresis and higher firmness for yoghurt with extruded microparticulate whey proteins.	Hossain et al. (2020)
Fat-free set-type yoghurts	Native or non-native whey protein	Fat replacement	The increase in gel strength measured in rheology with increasing native whey protein concentrations was perceived by consumers in ranking test.	Lesme et al. (2019)
3 months aged Cheddar cheese	Fat mimetics based on milk proteins	60% fat replacement	Significant differences in instrumental colour indices, few differences in firmness value and low flavour score for cheese with protein-based fat substitutes	Drake et al. (1996)
2 months aged Cheddar cheese	Whey protein microgels	50% fat replacement	Higher hardness value and moisture content and lower yield, “flavour” and “creaminess” descriptors score for cheese with whey protein ingredient.	Wen et al. (2021)
Spread and petit-suisse cheeses	Microparticulated whey proteins	Fat replacement	Lower intensity of “aroma” sensory attribute for cheese with whey proteins.	Sánchez-Obando et al. (2020)
Non-dairy-based foods				
Vermicelli pasta	Milk protein fortification	Increase the protein content	4% milk protein addition ensured acceptable sensory properties.	Niturkar et al. (1992)
Vermicelli pasta	Whey protein concentrate (5–10%)	Increase the protein content	Less yellowness and stickier pasta for more than 5% added milk protein. Increased cooking loss (6.0–8.4%) with the increase in the level of protein in the vermicelli pasta.	Prabhasankar et al. (2007)
Pasta	Milk protein (5–25%) fortification	Increase the protein and reduce starch level	Volume expansion and overall acceptability score of pasta (5% enrichment level) similar to pasta without protein addition.	Savita et al. (2013)
Bread	Milk protein	Partial flour replacement	Development of an optimal bland (16% milk protein). No difference in water absorption compared to control (0% milk protein). Longer dough development time and lower softening degree value for optimal bland sample.	Benali et al. (2021)
Biscuits	Sodium caseinate or whey protein concentrate	Partial flour replacement	Shrinkage of biscuits (whey protein) during baking or larger size of biscuits (sodium caseinate) compared to control. Higher hardness value (for more than 10% protein addition).	Gallagher et al. (2005)
Cookies	Whey and casein protein hydrolysates	Partial flour replacement	Cookies with 5% protein hydrolysates gave the most similar values to biscuits with no added proteins in terms of farinographic indices. Significant increase in hardness values.	Gani et al. (2015)
Cookies	Whey protein encapsulated with black currant	Partial flour replacement and phenolic enrichment	Higher hardness values, diameter and baking loss percentage. Higher value of total phenolic compounds and DPPH antioxidant capacity.	Wu, Hui, Stipkovits, et al. (2021)
Cake	Whey protein isolate and hydrolysed	Protein enrichment (0–30%)	No significant differences in hardness for all cakes. 30% enrichment was perceived as different from control by sensory analysis, in terms of texture attribute.	Camargo et al. (2018)
Cake	Whey protein concentrate	Partial flour replacement (5.6 and 6.5%)	Increase in the hardness of cake. Specific volume and baking loss improvement. Better sensory scores for 5.6% protein addition.	Ammar et al. (2021)

4.1.1. Yogurt

Yogurt is obtained from the controlled fermentation of milk by symbiotic cultures of strains of *Streptococcus thermophilus* and *Lactobacillus delbrueckii* subsp. *bulgaricus*, which must have a number of colonies of at least 10^7 CFU/g until the end of the shelf life (Codex Alimentarius, 2003; MacBean, 2009). The development of functional yogurts has mainly involved the addition of probiotics (Fazilah, Ariff, Khayat, Rios-Solis, & Halim, 2018) and the reduction of fat (Atallah, Morsy, & Gemiel, 2020). However, reducing the fat content of yogurt can cause undesirable flavour and creaminess properties. A recent review addressed the study of the flavour retention capacity, texture and sensory perception of low-fat yogurt formulated with milk proteins (Lesme, Rannou, et al., 2020). The authors emphasised the use of whey protein aggregates, ingredients with customised functionality, in low-fat yogurt. Their addition to low-fat yogurt affects both the texture and aroma perception due to the modification of viscosity and hardness and thanks to milk protein-aroma interactions. The authors state that the sensory modalities (texture, aroma and taste) interfere with each other and can be cognitively associated, corroborating the hypothesis of modulating the multisensory perception of flavour by exploiting the interaction between milk proteins and components of the food matrix.

Through sensory tests on samples of low-fat yogurt developed with the addition of different blends of milk proteins as fat replacers, JanhØJ, Petersen, FrØSt, and Ipsen (2006) found that the mixture containing microparticulated whey proteins received the best scores in terms of sensory creaminess, similar to the control yogurt sample (3.5% milk fat, without replacer). Microparticulated whey protein added to low-fat yogurt improved its texture and rheological properties, reducing serum separation upon centrifugation (Torres, et al., 2018). Hossain, Keidel, Hensel, and Diakité (2020) suggested the possibility of controlling the size of microparticulated whey protein particles by extrusion treatment in order to improve the creaminess of low-fat yogurts. In fact, because of their small particles (d50 < 3 μm), microparticulated whey proteins are perceived as most similar to fat globules on the tongue, imparting a creamy texture (Hossain, et al., 2020).

By adding whey protein aggregates from 0.1 to 1% in fat-free yogurt, obtained by thermal treatment of whey proteins, Lesme et al. (2019) showed a reduction in syneresis of up to 40%. In fat-free yogurts, whey protein aggregates showed also a slow release of more hydrophobic volatile molecules such as 2-nonanone and methyl cinnamate (Lesme, Alleaume, et al., 2020).

Araújo dos Santos, et al. (2022) produced Greek yogurt with goat's milk and yam extract and enriched it with goat's milk casein powder. The addition of casein powder increased the viscosity of yogurts. The best scores on acceptance, purchase intention, and preference tests were shown by Greek goat yogurt enriched with casein powder but without yam extract.

Most of the work has primarily focused on texture and physical properties, although recent attention is increasing on the use of "tailored" milk proteins to bind volatile compounds of food in order to manage their release and perception.

4.1.2. Ice cream

Ice cream is the most typical frozen dairy dessert, consumed worldwide. The use of milk proteins in ice cream mainly concerned the replacement of part of the fat of ice cream (Akbari, Eskandari, & Davoudi, 2019). Ice cream contains about 12% of fat, which performs important functions for the structure and flavour of product.

A recent review addressed the development of functional ice cream and the implications on sensory properties caused by the addition of milk proteins to develop a low-fat ice cream (Genovese, Balivo, Salvati, & Sacchi, 2022). The authors also reviewed the use of bioactive peptides as additional ingredients in ice cream formulation. Milk proteins have been found to be useful in compensating for the loss of solid fats and they can improve mouthfeel, creaminess and aroma retention in reduced-fat ice cream. However, the best performance has been achieved when the replacement of fat with milk protein resulted in partial replacement, approximately 50% replacement. Interestingly, functional ice cream could also act as a source of bioactive peptides derived from the use of milk proteins as ingredient.

Table 1 offers an insight of the use of milk proteins in the development of functional ice cream, with the main results on physical properties and sensory perception.

4.1.3. Cheese

Cheese can contain more than 30% fat. Due to its high fat, cholesterol and calorie content, cheese has attracted the attention of many food scientists to reduce its fat content, by generally replacing it with milk protein ingredients, trying to ensure adequate yield and sensory quality.

Fat reduction in cheese not compensated by the addition of suitable substitute ingredients is associated with unacceptable physical properties, e.g. harder texture (Ningtyas, Bhandari, Bansal, & Prakash, 2017), and poor cheese flavour (Hinrichs, 2001). Furthermore, the lower yield could make the production of low-fat cheese unprofitable. Therefore, the addition of fat substitutes, particularly whey protein, has been investigated.

The addition of microparticulated whey proteins in low-fat Cheddar cheese formulation compared to low-fat Cheddar cheese without fat replacer improved yield and texture properties (Stankey, et al., 2017). In 3-months aged Cheddar cheese, the use of Dairy Lo®, a microparticulated whey protein-based fat substitute, caused significant differences in instrumental colour indices but few differences in the firmness value (average values of 6.13 N for low-fat cheese and 6.73 N for the whole one) (Drake, Boylston, & Swanson, 1996). Full fat cheese also received higher flavour intensity scores. Similar result on hardness was obtained in Caciotta cheese with 75% less fat made with microparticulated whey protein concentrate (Di Cagno, et al., 2014). In another study, the reduced-fat Caciotta cheese, developed with Simplesse®, the first commercially available microparticulated whey protein product, showed lower aroma intensity (Turin & Bonomi, 1995). In 60 days aged 50% reduced-fat Cheddar cheese produced with the addition of whey protein microgels gave significantly lower yields and higher moisture content than full fat Cheddar cheese (Wen, et al., 2021).

The addition of microparticulated whey proteins to replace fat in spread and Petit-Suisse cheeses, already for a 10% fat replacement, caused a significant increase in the viscosity of low-fat cheeses (Sánchez-Obando, Cabrera-Trujillo, Olivares-Tenorio, & Klotz, 2020). In addition, a fat reduction between 10 and 40% ensured good acceptability in the sensory test, providing not differences in the aroma, flavour and texture descriptors compared to the control cheese.

In general, the replacement of fat with whey protein ingredients caused a reduction in the yield and a higher moisture content of the cheese. However, an aspect lacking in the literature, that should be considered, is the development of low-fat cheese using casein.

Fat plays an important role in ripened cheese both as precursor of aroma compounds and in their retention and release. For this reason, the sensory characteristics of cheese (texture, taste, odour and aroma) could be negatively affected, especially for high percentages of fat replacement. Based on these results, the most suitable choice to maintain adequate sensory characteristics during the consumption of the cheese could be the partial replacement of the milkfat with whey protein and casein as well as the optimisation of the formulation through the use of different substitutes, also fat-based substitutes (e.g. fats rich in unsaturated fatty acids).

4.2. Non-dairy foods

Milk proteins, both whey protein and casein, have usually been employed in cereal-based foods to increase and improve the content and quality of proteins. Milk proteins are also used in biscuits and cakes to partial replace the fat or the flour, to have low fat and low carbohydrates foods, respectively. Furthermore, whey proteins act as surfactants by developing food emulsions.

4.2.1. Pasta and bread

For daily use and consumption at all ages, as well as advantages such as low cost, convenience and a long shelf life (Bustos, Perez, & Leon, 2015), pasta is a suitable product to be functionalised with milk proteins, both to improve the biological value of the proteins and to improve the functional performance of the pasta. For example, milk protein isolate, whey protein and caseinate are usually added to gluten-free pasta doughs to compensate for the deficiency of the gluten network with the aim of improving the structure of the product (Collar, 2018).

Savita, Arshwinder, Gurkirat, and Vikas (2013) evaluated the sensory and cooking quality of pasta enriched with different sources of added proteins (milk, legumes and eggs). Regarding milk proteins (whey proteins and caseins), the best performances were obtained with an enrichment level of 5% of whey protein concentrate, with a volume expansion and overall acceptability score of pasta similar to the control sample without whey proteins. Niturkar, Doke, Joglekar, and Rotte (1992) had previously reported that the optimal level of milk protein fortification of vermicelli pasta was 4%, which provided the best performance in terms of organoleptic characteristics. Similarly, Prabhasankar, Rajiv, Indrani, and Rao (2007) found that adding more than 5% of milk protein concentrate in vermicelli pasta resulted in a less yellowness and stickier pasta. Generally, cooking loss has been found to increase as the level of milk protein concentrate enrichment increases (Mann & Malik, 1996; Prabhasankar et al., 2007), due to an interference of the gluten structure by milk proteins.

Comparable results were obtained in bread dough (Zadow, 1981), where the addition of milk protein concentrate offered a weaker and less elastic dough, which retained less carbon dioxide during leavening due to the non-optimal gluten network formation. The addition of yogurt and cheese curds as a partial replacement for flour provided good sensory acceptability, assessed by a panel of 25 untrained participants, particularly for bread with 50 g of yogurt and 30 g of curd cheese (Graça, Raymundo, & Sousa, 2019). The extension properties of dough after 60 min of leavening time at 30 °C did not differ from the control sample for lower yogurt addition values (50 g), while the addition of cheese curd gave a significant difference already at minimal levels of addition, reducing the extensibility of the dough. Benali et al. (2021) developed bread made from wheat flour, chickpea flour and milk powder. They reported that the optimal blend consisted of 60% wheat flour, 24% chickpea flour, and 16% milk powder. Water absorption did not differ between the control and the optimal blend dough, although bread with the optimal blend required a longer dough development time and had a lower softening degree value. Among the six sensory attributes tested by a panel of 30 semi-trained members, no significant differences were reported for “crumb” and “chewiness” descriptors.

4.2.2. Cookie

Wheat flour is the main ingredient in biscuit making. Compared to the production of bread or long-leavening products, flour with a lower protein and gluten content is preferred to produce biscuits. Cereal proteins are low in the essential amino acid lysine, which makes them of low biological value when consumed on their own. Using milk proteins in wheat dough can help increase the biological value of cookie proteins. Gallagher, Kenny, and Arendt (2005) studied the influence of milk protein enrichment (sodium caseinate and whey protein), added at levels of 5, 10 and 15% of flour weight, on the characteristics of dough and baked biscuits. Whey protein concentrate caused the biscuits to shrink during baking, while biscuits containing sodium caseinate were significantly larger than the control without protein powders. Moreover, adding more than 10% of sodium caseinate increased the hardness of the biscuits. The cookies developed with 5% whey and casein hydrolysates provided a similar values, compared to the control biscuits (0% added proteins), in terms of farinographic indices while an addition greater than 10% caused significant differences (Gani, et al., 2015). The use of milk proteins, already from 5% addition, caused a significant increase in hardness values. The sensory texture values of the samples assigned by panellists were in good agreement with the instrumental texture values and the most accepted cookies were those formulated with 5% milk proteins. The replacement of 5–15% of flour with whey protein encapsulated with black currant increased the content of total phenolic compounds and DPPH antioxidant capacity, as well as increased biscuit hardness as the amount of substitution increased (Wu, Hui, Stipkovits, et al., 2021).

4.2.3. Cake

Some applications have seen the use of milk proteins as replacer for wheat flour and eggs in cakes with the aim of reducing the amount of carbohydrates or lipids, respectively, by emulating the emulsifying, gelling and foaming properties. Jyotsna, Sai Manohar, Indrani, and Venkateswara Rao (2007) studied the rheological and baking properties of eggless cakes made with 10, 20 and 30% whey protein concentrate as a replacement for eggs and wheat flour. The increase in the percentage of protein caused a better distribution of air bubbles in the cake batter (smaller size and greater uniformity of distribution), although the 20% whey protein concentrate addition ensured the maximum improvement in specific loaf volume of eggless cake. The use of whey protein concentrate as egg substitutes in cake could be improved when supplemented with guar and xanthan gums, in terms of sensory and physicochemical properties (Ayoubi, Habibi, & Karimi, 2009). Therefore, once again the combination of different substitutes helps to improve the functional performance.

In general, height and volume of the cakes increased with increasing protein content (Camargo, et al., 2018). Compared to control sample, the cakes had no significant differences in sensory and instrumental hardness and colour, except a significantly different higher a* value in the sample with the higher % protein addition, probably caused by an increased Maillard reaction. Ammar et al. (2021) developed a gluten-free cake fortified with whey protein at a maximum addition percentage of 6.5%. Specific volume and baking loss of cakes were improved, although hardness was increased. In terms of overall sensory intensity descriptor, the cakes with the lowest addition of whey proteins concentrate (5.6%) obtained a score not significantly different from the control sample.

Non-dairy foods formulated with milk proteins deserve more attention in the literature. Generally, the use of whey protein concentrate rather than isolate or microparticulate has been contemplated. However, milk proteins can offer many customised properties and studying other milk protein ingredients in the formulation of pasta, biscuits and cakes could help improve the sensory properties of the end products.

4.2.4. Whey protein stabilised emulsions

An emulsion involves the presence of a dispersed phase and a continuous phase. Whey proteins act as emulsifiers, providing physical stability to the emulsion, by placing themselves at the interface between the two phases (Lam & Nickerson, 2013). Additionally, whey protein is known for its gelling ability, further improving the stability of the emulsion.

It has been shown that the peptide size and hydrophobicity are important in emulsion physical stability, and small peptides ($<$5 kDa), e.g. hydrolysed proteins, form a weak interfacial film and unstable emulsions (Schröder, Berton-Carabin, Venema, & Cornacchia, 2017). A good crosslinking of the protein gel network is essential for good functional performance of milk protein emulsion gels (W. Fu et al., 2018). The rheological and structural properties of whey protein gels are improved by some pre-treatments, such as enzymatic treatment with transglutaminase, high-intensity ultrasound treatment or interaction of milk proteins with calcium ions. These treatments are responsible for the formation of covalent crosslinks between amino acid residues in the milk protein structure, increasing the viscosity and improving the texture of whey protein gels. In addition, the interaction between volatile compounds and milk proteins modifies the structure of the protein and consequently its functional properties. In fact, as shown by W. Fu et al. (2018) the interaction between whey protein and cinnamaldehyde (responsible for the cinnamon odour) reduces the syneresis in whey protein gels. This structural change of whey protein-based emulsion gel can also act as vehicles for controlling the release of bioactive compounds in foods (Guo, Bellissimo, & Rousseau, 2017; Lu, Mao, Hou, Miao, & Gao, 2019). For example, the increase in β-fold structure of whey proteins from 47.2% to 72.9% in the presence of cinnamaldehyde increased the in vitro bioaccessibility of β-carotene from 27.54% to 59.87% (R. Zhao et al., 2022). Therefore, the development of emulsion stabilised with whey protein and with the addition of certain aroma compounds could be a good strategy to improve the absorption and metabolism of bioactive compounds in humans, e.g. in the case of foods rich in carotenoids.

Some works have also investigated the release of volatile compounds in emulsions, both in vivo analysis or by simulating the oral condition, with the aim of understanding the release of aroma compounds after the interaction between whey proteins and saliva. Saliva produces a higher release of hydrophobic volatiles and lower release of hydrophilic volatiles. This result was attributed to dilution effect and saliva-induced emulsion instability (Mao, Roos, O'Callaghan, & Miao, 2013).

This behaviour was also found in an oil-in-water model dispersion obtained adding refined olive oil spiked with virgin olive oil phenolic compounds to a whey protein solution. This study investigated the release of some aroma compounds in the presence of human saliva and established that the higher level of olive oil phenolic compounds positively affected the extent of aroma release (Genovese, Caporaso, De Luca, Paduano, & Sacchi, 2015).

Although the above studies involved model whey protein emulsion systems, they pave the way for the design of novel functional foods formulated with whey protein that can act as emulsifiers, fat substitutes, etc., offering good sensory properties and health benefits such as the highest aroma persistence, the creation of a new sensory experiences in foods or better bioavailability of bioactive compounds during digestion.

5. Conclusion and perspectives

The aim of this review was to offer the reader interesting insights to optimise the use of milk proteins in the development of functional foods considering the sensory implications. Milk proteins can be versatile ingredients for developing functional foods, ensuring health benefits and adequate sensory properties. The interaction between milk proteins and volatile compounds could bind aroma compounds helping to manage their release kinetics in reduced-fat foods. However, the aroma persistence during in vivo consumption also depends on the interaction with saliva components, which could cause a different release of volatile compounds. In this regard, further studies focused on in vivo aroma perception of foods functionalised with milk protein are desirable.

Milk proteins also interact with phenolic compounds, mitigating their astringency, pungency and bitterness. The bioavailability of phenolic compounds interacting with milk proteins is controversial, as it depends on the chemical composition of the type of protein and the type of phenolic compound.

These interactions between milk proteins and food matrix components can change the protein structure imparting new functional properties. In fact, recent interests are focused on the use of technological treatments to develop more compatible milk protein-based ingredients for tailored food applications, such as the design of protein-polyphenols nanoparticles that could enhance the delivery and bioaccessibility of these bioactives or the development of whey protein-based emulsion systems that could broaden the range of control of the release of volatile compounds. Therefore, based on the type of food product and its formulation, different types of milk proteins can offer customised functional properties, greatly increasing their applications in functional foods.

Furthermore, the development of bioactive peptides from milk proteins by gastrointestinal digestion, enzymatic hydrolysis or microbial fermentation is worthy of consideration. Peptides generated by protein hydrolysis could bring a bitter taste to functional food, hence the sensory properties of such milk protein peptide-enriched functional products should be taken into consideration. Further studies investigating the in vivo biological activity of bioactive peptides derived from milk proteins, as well as the flavour perception during oral processing of these functional foods, would be recommended.

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